Geoacoustic Parameters of Marine Sediments: Theory and Experiment

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LONG-TERM GOALS

Based on at-sea experiments and the development of new theories, the long term objective is to characterize rigorously the inter-relationships that exist between the geo-acoustic properties (*i.e.*, sound speed, sound attenuation, shear speed, shear attenuation, density, porosity, grain size, grain shape and overburden pressure) of saturated, unconsolidated granular media such as marine sediments.

OBJECTIVES

The scientific objectives of the sediment research are eightfold.

(1) Develop my recently introduced Doppler Spectroscopy technique for estimating the geo-acoustic properties of marine sediments using a high-Doppler airborne sound source.

(2) Continue refining my analytical theory of wave propagation in saturated granular materials.

(3) Develop an analytical theory of wave propagation in a 2-layer (Pekeris) waveguide with an attenuating bottom.

(4) Develop an analytical model of wave propagation in a 3-layer waveguide (atmosphere-ocean-sediment) from a high-Doppler airborne source.

(5) Develop causal theory of pulse propagation in a viscous fluid.

(6) Numerical (forward) modeling of the three-dimensional sound field from a high-Doppler sound source in a multi-layer ocean waveguide.

(7) Develop inversions, based on the numerical forward model, for extracting sediment parameters and sub-bottom structure from Doppler Spectroscopy data.

(8) Identify the relationships between the geometrical properties of individual grains (*e.g.*, grain size and grain shape) and the physical properties of the bulk granular material (*e.g.*, porosity).

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14. ABSTRACT **Based on at-sea experiments and the development of new theories, the long term objective is to characterize rigorously the inter-relationships that exist between the geo-acoustic properties (i.e., sound speed, sound attenuation, shear speed, shear attenuation, density, porosity, grain size, grain shape and overburden pressure) of saturated, unconsolidated granular media such as marine sediments.**		
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In addition to sediment research, the low-frequency sound from the collective oscillations of a bubble plume formed by a plunging water jet has been investigated, with a view to understanding the mechanisms responsible for producing naturally generated, low-frequency ambient noise in the ocean.

On a more abstruse level, we are working with Prof. Giorgio Gratta, Stanford, in an attempt to detect extremely high energy neutrinos from their acoustic signature in the ocean, using the US Navy's AUTEC array of hydrophones off Andros Island, Bahamas.

APPROACH

1) Doppler Spectroscopy

This is a new technique for measuring the low-frequency (100 Hz to 1 kHz) sound speed in marine sediments in which a high-speed airborne sound source ensonifies the ocean and the sediment. Most of the received sound is in the form of harmonics extending from about 80 Hz up to 1 kHz. As the source approaches toward (recedes from) the sensor station, the harmonics are Doppler up-shifted (down-shifted), as illustrated in the spectrograms in Fig. 1. Normal modes are excited in the water column and are detected on our autonomous line array of 11 non-uniformly spaced hydrophones. A high-resolution spectrum of a harmonic at approximately 80 Hz from just one of the phones (Fig. 2) exhibits sharp peaks, representing the Doppler up- and down-shifted modal field. The magnitude of the modal shifts depends on the speed of the source and, critically, the properties of the sea bed. From a precision measurement of the shifted modal frequencies, an inversion returns the sound speed in the sediment; and the remaining geo-acoustic parameters are determined from their known correlations with the sound speed. Two of my graduate students, Eric Giddens and Melania Guerra, have been directly involved in our Doppler Spectroscopy research, along with my engineer, Fernando Simonet. One of my earlier graduate students, Dr. Thomas Hahn, who now holds a faculty position at the University of Miami, assisted us during our participation in SAX04.

2) Grain-shearing theory of the wave properties of sediments

My grain-shearing theory of the wave properties of saturated granular materials such as marine sediments is becoming internationally recognized as an alternative to the Biot theory in which the loss mechanism is viscosity of the pore fluid. The grain-shearing theory is derived from the linearized Navier-Stokes equations and is based on the micro-physics of sliding at grain-to-grain contacts. The theory is analytical, yielding simple algebraic expressions for the compressional and shear wave speeds and attenuations as functions of the physical properties (porosity, density and mean grain size) of the sediment. Essentially, the theory predicts compressional and shear attenuations that increase linearly with frequency and corresponding wave speeds that show weak dispersion, varying logarithmically with frequency.

3) Theory of acoustic propagation in a 2-layer waveguide with an attenuating bottom

Based on multiple integral transforms, a solution of the Pekeris problem is obtained for the case when attenuation in the bottom is significant. A method of solving the dispersion relationship for the complex eigenvalues is introduced, based on the familiar Newton-Raphson iterative technique. A new type of proper mode is identified that exists solely because of attenuation in the bottom. Various asymptotic approximations to the EJP branch line integral are developed.

4) Analytical theory of a high-Doppler source in a 3-layer waveguide

An analytical theory of sound in a 3-layer waveguide (atmosphere, ocean and sediment) from a high-Doppler airborne source is being developed. Multiple integral transform techniques have been used, in conjunction with the appropriate boundary conditions, to return a new dispersion relation that includes

the effects of a moving airborne source. The analytical solution provides a useful check for the numerical model of a high-Doppler source in a similar multilayer environment.

5) Causal theory of pulse propagation in a viscous fluid

Stokes' published an equation for wave propagation in a viscous fluid in 1845 and since then its solutions for harmonic waves have been well documented. With regard to pulse propagation, however, it has been (incorrectly) called into question on several occasions over recent years on the grounds that it predicts non-causal arrivals. Such claims are based on approximate solutions to Stokes' equation. To investigate the properties of pulses predicted by Stokes' equation, I performed an analysis of the Green's function, using multiple integral transforms. The result shows that Stokes' equation is perfectly well behaved, predicting pulse arrivals that are causal in the strict sense of having no arrivals before the source is activated and no instantaneous arrivals. The failure to satisfy causality in previous analyses of Stokes' equation stemmed from poor quality approximations to pulse solutions, not from any intrinsic defect of the equation itself.

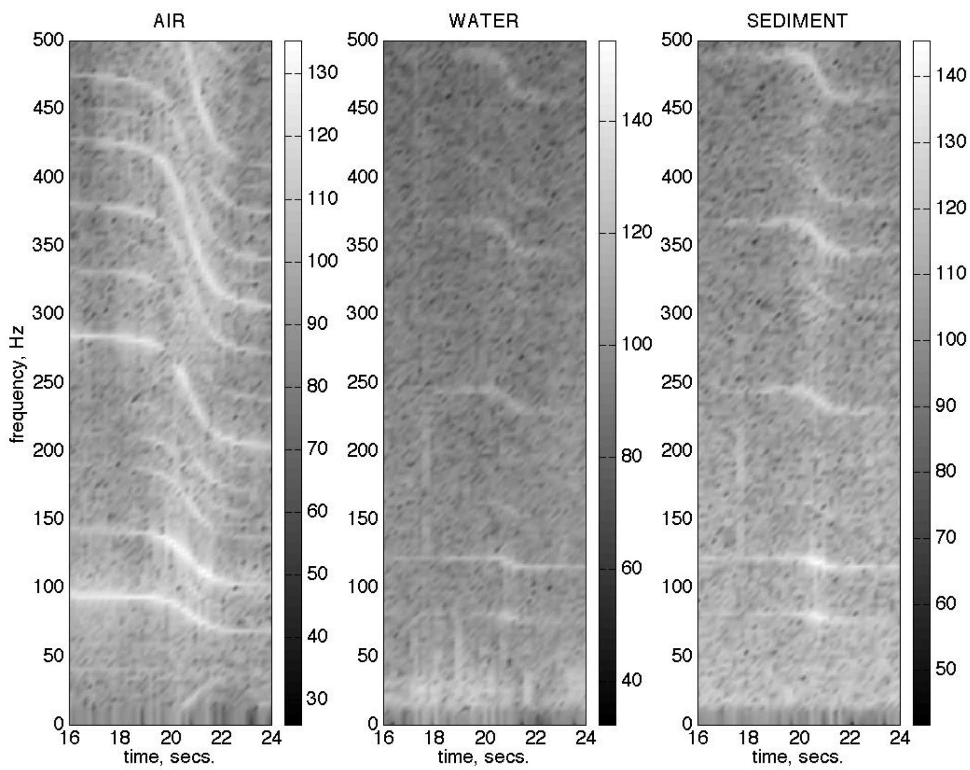

Figure 1. Spectrograms showing Doppler-shifted harmonics from a fast airborne source as it passes over the sensor station. (Gray scale is in arbitrary dB). The data were collected on 20 October 2003 in shallow water north of Scripps pier.

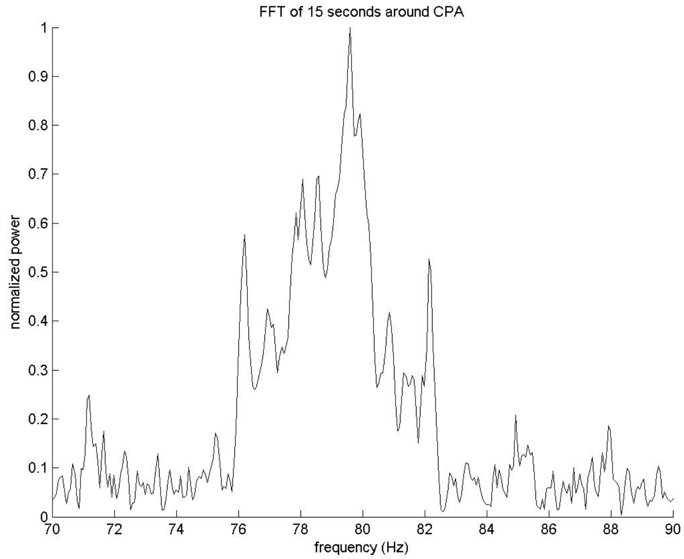

Figure 2. High-resolution spectrum of a low-order harmonic in the water column. The peaks at 82 and 76 Hz, respectively, represent mode 1, up- and down-shifted as the source approaches and departs. The data were collected on 20 October 2003 in shallow water north of Scripps pier.

6) Numerical (forward) modeling of the sound field from a high-Doppler source in a multi-layered waveguide

As the basis of an inversion technique for determining sediment properties from our Doppler Spectroscopy experiments, a 3-dimensional wavenumber-integral acoustic propagation model has been developed which yields the sound field in the atmosphere, ocean and sediment from a high-Doppler, non-accelerating airborne source. This work was performed mainly by my graduate student, Eric Giddens. One of the interesting features that emerges from the model is the asymmetry that exists in the sound field ahead of and behind the rapidly moving source.

7) Geoacoustic inversions for Doppler Spectroscopy

Based on a comparison of the predictions from wavenumber integral forward model and the data obtained from our Doppler Spectroscopy experiments, a "best match" is obtained, from which the sediment parameters are estimated. Essentially, a cost function is formed and minimized. This work was performed mainly by my graduate student, Eric Giddens.

8) Grain shape and sediment porosity

Of all the physical properties, it could be argued that the porosity of a sediment is by far the most important in determining its wave properties. The porosity is related to the mean grain size, although not uniquely, suggesting that another parameter is involved, perhaps grain shape or roughness. By examining the shapes of individual grains under a microscope, with careful analysis of the resultant computer-generated images, the relationships between mean grain diameter, rms roughness and bulk-sediment porosity are being investigated. This work is being performed by my new graduate student, David Barclay.

WORK COMPLETED

1) Doppler Spectroscopy field experiments

During October 2004, we performed Doppler Spectroscopy experiments as part of the ONR-sponsored SAX04 off Fort Walton Beach, northern Gulf of Mexico; and as this report is being written, we are preparing similar experiments, as well as ambient noise measurements, which will constitute our component of the MAKAI experiment to be conducted off the west coast of Kauai in September 2005. We have also conducted half a dozen Doppler Spectroscopy experiments at a site about 1 km north of Scripps pier, where the sub-bottom structure is known independently from the extensive geophysical surveys of Driscoll & Hogarth, SIO. In all these experiments, the sensor in the water column was our Fly-By line array of 11 non-uniformly spaced hydrophones. This array has been used in a vertical configuration and lying horizontally on the seabed, where it was left for some six weeks with no adverse effects. The Fly-By array is now fully autonomous, driven by a bank of lithium-ion batteries, with an internal hard drive for recording all the channels and an RF link allowing remote downloading of the data. Integrated into the line are a tilt sensor and flux-gate compass; and a microphone is mounted about 1 m above the upper flotation unit for recording airborne sound.

2) Grain-shearing theory of the wave properties of sediments

Recently, the dependence of the wave properties on various physical parameters (*e.g*., shear speed versus depth in sediment), as predicted from the grain-shearing theory, were compared in detail with extensive data sets on compressional and shear waves culled from the literature. With no adjustable parameters available, excellent agreement was found on essentially all counts, as reported in a paper in the *Journal of the Acoustical Society of America*.

3) Theory of acoustic propagation in a 2-layer waveguide with an attenuating bottom

This work is complete and has been submitted for publication in the *Journal of the Acoustical Society of America*.

4) Analytical theory of a high-Doppler source in a 3-layer waveguide

The analysis is complete and a paper has been written which is about to be submitted for publication in the *Journal of the Acoustical Society of America*.

5) Causal theory of pulse propagation in a viscous fluid

The analysis is complete and a paper has been accepted for publication in *Physical Review E*.

6) Numerical (forward) modeling of the sound field from a high-Doppler source in a multi-layered waveguide

The numerical model is complete and has been described fully in Eric Giddens' PhD thesis.

7) Geoacoustic inversions for Doppler Spectroscopy

The geoacoustic inversion technique is complete and has been described fully in Eric Giddens' PhD thesis.

8) Grain shape and sediment porosity

This is new work which is progressing rapidly.

RESULTS

1) Doppler Spectroscopy field experiments

Several data sets collected at the fine-sand experiment site north of Scripps pier have been inverted, each of which yields a full compliment of sediment parameters. For instance, at a frequency of 80 Hz, the values returned for the geoacoustic parameters are: sound speed ≈ 1634 m/s; sound attenuation ≈ 0.0095 dB/m (= 0.12 dB/m/kHz); sound speed ratio ≈ 1.0769; shear speed ≈ 94 m/s; shear attenuation ≈ 3.1 dB/m (= 39 dB/m/kHz); density ≈ 2019 kg/m^3; porosity ≈ 0.4123; and mean grain diameter ≈ 83.4 μm. On comparison with measurements made at higher frequencies by other researchers in similar sediments, these results are consistent with a weakly dispersive sound speed and a sound attenuation that varies linearly with frequency. (Paper in preparation)

2) Grain-shearing theory of the wave properties of sediments

The grain-shearing theory predicts relationships between wave and physical properties of marine sediments that match experimental measurements on all types of granular materials, ranging from the finest clays to the coarsest sands. This agreement goes well beyond simple dispersion and attenuation as functions of frequency, covering, for example, shear speed as a function of depth in the sediment, sound speed as a function of porosity, and all other combinations of wave and physical properties. One important fact that emerges from the theory is that the sound speed and attenuation in the coarser sands are highly sensitive to the porosity. [JASA, **117**, 137-152, (2005)]

3) Theory of acoustic propagation in a 2-layer waveguide with an attenuating bottom

A new type of proper normal mode is identified, designated a “dissipation” mode, that arises solely from the presence of attenuation in the bottom. Dissipation modes are exact solutions of the wave equation which also satisfy the radiation condition at great depth in the basement. In the absence of bottom loss, the only proper modes in the problem are the conventional trapped modes, but as the attenuation in the bottom rises, the total number of proper modes supported by the channel increases approximately linearly with the bottom loss. [JASA, conditionally accepted]

4) Analytical theory of a high-Doppler source in a 3-layer waveguide

The newly derived dispersion relation, which includes Doppler shifts, predicts significant asymmetry in the modal structure of the sound field fore and aft of the moving source. Under appropriate conditions, the up-shifted frequency ahead of the source gives rise to more modes in the channel than the down-shifted frequency behind the source. The frequency shifts experienced by the modes form the basis of our Doppler Spectroscopy geoacoustic inversion technique. (Paper complete and about to be submitted to JASA)

5) Causal theory of pulse propagation in a viscous fluid

The solutions of Stokes’ equation for pulse propagation in a viscous fluid have been shown to satisfy causality in a very strict sense: there are no arrivals before the source is activated at $t = 0$, nor are there any instantaneous arrivals. For the first time, it is shown that everywhere in the fluid at $t = 0$, the pulse is perfectly smooth in the sense of being *maximally flat*, that is, the pulse and all its time derivatives are identically zero. [Phys. Rev. E, in press]

6) Numerical (forward) modeling of the sound field from a high-Doppler source in a multi-layered waveguide

This is a component of the inversion procedure that has yielded results such as those cited in sub-section 1) above.

7) Geoacoustic inversions for Doppler Spectroscopy

This is a component of the inversion procedure that has yielded results such as those cited in sub-section 1) above.

8) Grain shape and sediment porosity

Preliminary results on a sample of sand from Candidasa Beach, Bali, indicate that the rms roughness of the grains scales with the mean grain diameter.

IMPACT/APPLICATIONS

My theoretical and experimental work on the wave and physical properties of marine sediments, and dispersive media in general, is broadly based and has gained a substantial following in the ocean acoustics research community. At ASA meetings and international conferences on acoustics, my theories are cited regularly, suggesting that the work is influencing other scientists in the way that they approach the complicated issues associated with wave propagation in granular materials.

TRANSITIONS

Several research groups in the USA and elsewhere are using the results of my theoretical work in their own programs, including investigators at the Applied Physics Laboratory, University of Washington, the University of Hawaii, NRL Washington D.C., NRL Stennis and in UK government research laboratories. This includes my work on ambient noise, theory of waves in sediments, acoustic propagation in shallow ocean channels, sound in multi-layer waveguides, and underwater sound fields from high-Doppler, airborne sources.

RELATED PROJECTS

U.S.A.

1. Dr. Michael Richardson, N.R.L., Stennis, and I are continuing to collaborate on the collection and interpretation of sediment wave-property data. In particular, we conducted nearly co-located measurements of sediment sound speed and attenuation in the Gulf of Mexico during SAX'04. His experiments covered the frequency band from 5 to 300 kHz and ours, as the basis of the Doppler Spectroscopy inversion technique, were from 80 Hz to 1 kHz. Chief Scientist for SAX'04 was Dr. Eric Thorsos, APL, University of Washington.

2. I have been working with Drs. Michael Porter and Martin Siderius in planning the MAKAI experiment to be conducted in September 2005 off the west coast of Kauai. We shall be deploying our Fly-By array at one deep (100 m) and one shallow (20m) site during MAKAI experiment. At both locations, the array will be used in the vertical configuration for ambient noise measurements, with a view to performing inversions for the bottom parameters. At the shallow site, the array will also be deployed horizontally on the seabed for recording the noise signature of a high-Doppler airborne sound source and these data will be used in our Doppler Spectroscopy inversions.

3. Prof. Giorgio Gratta, Stanford, and I are continuing research on the underwater acoustic detection of extremely high energy neutrinos. Acoustic data for this project are being provided by the U.S. Navy's AUTEC range off Andros Island, Bahamas.

4. Prof. H. K. Cheng, University of Southern California, and I are collaborating on research to investigate sonic booms underwater. He is developing a theory of the shear wave excited in the sediment by a sonic boom, using my theory of waves in sediments as a central element of his analysis.

Canada

1. Prof. Ross Chapman, University of Victoria, B.C., and I are collaborating on a shallow water experiment aimed at determining low-frequency (100 Hz to 1 kHz) sound speed and attenuation in marine sediments. In particular, we shall try to use the head wave for extracting the required information. For this frequency band, Ross has a low-intensity air gun source and we use an airborne source of opportunity, two completely different ways of exciting the head wave, but which should yield compatible answers.

United Kingdom

1. Prof. Tim Leighton, Institute of Sound and Vibration Research, University of Southampton, and I are discussing several joint research projects on underwater acoustics. These will involve the inter-change of graduate students, post-docs and perhaps more senior staff between ISVR and SIO.

2. Dr. Nicholas Pace, University of Bath and I are discussing the possibility of using an airborne source for low-frequency measurements of sediment properties in the Mediterranean.

3. Nathan Price and Gareth Somerset, SEA Ltd. are developing a system for inverting ambient noise measured on a vertical line array to obtain sediment parameters. Their system uses the vertical coherence of ambient noise, as I proposed some years ago, combined with my recent theory of waves in sediments, to yield the majority of sediment properties.

4. Dr Alastair Cowley, DERA, Winfrith is continuing to collaborate with me on phased array techniques applied to acoustic daylight imaging. Several years ago, his team of engineers conducted tests in San Diego Bay using our ADONIS array head of 128 hydrophones with their high-speed beamformer. This phased array system, without the spherical reflector that we used in our original acoustic daylight experiments, yielded recognizable images of targets at ranges of approximately 10 m solely from the acoustic illumination provided by the ambient noise in the ocean.

PUBLICATIONS

Journals & Chapters in Books

1. M. J. Buckingham and E. M. Giddens, "On the acoustic field in a Pekeris waveguide with attenuation in the bottom half-space", *J. Acoust. Soc. Am.*, (2005) [conditionally accepted, refereed]

2. M. J. Buckingham, "Causality, Stokes' wave equation and acoustic pulse propagation in a viscous fluid", *Phys. Rev. E.*, (2005) [in press, refereed].

3. M. J. Buckingham, "Compressional and shear wave properties of marine sediments: comparisons between theory and data", *J. Acoust. Soc. Am.*, **117**, 137-152 (2005) [published, refereed].

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4. M. J. Buckingham, “From air to sea to sediment: aircraft sound for ocean-acoustics experiments”, Conference Honouring Prof. John Papadakis on the Occasion of His Retirement, Heraklion, Crete, November 2004 [INVITED].

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PATENTS

1. M. J. Buckingham, "Method and apparatus for measuring the speed and attenuation of sound", 28 November 2003 [provisional]

HONORS/AWARDS/PRIZES

My graduate student, Eric Giddens, successfully defended his Ph.D. on 6 May 2005. He was also awarded the following two prizes by the Acoustical Society of America.

1) First Prize for Best Student Paper, awarded by the Underwater Acoustics and Engineering Acoustics Technical Committees at the 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 December 2002: "Sound from a light aircraft for underwater acoustic applications".

2) First Prize for Best Student Paper, awarded by the Acoustical Oceanography Technical Committee at the 148th Meeting of the Acoustical Society of America, San Diego, California, 15-19 November 2004: "Geoacoustic inversions in shallow water using Doppler-shifted modes from a moving source".

I was the Technical Chair of the 148th Meeting of the Acoustical Society of America, San Diego, California, 15-19 November 2004.